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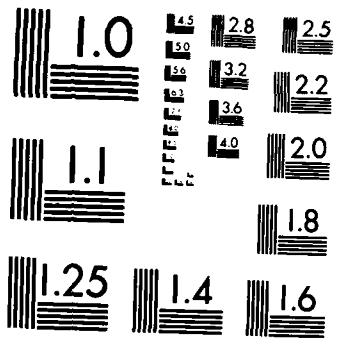

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A PRELIMINARY COMPARISON OF THE TRANSIENT EFFECTS OF SINGLE VERSUS MULTIPLE Q-SWITCHED DOUBLED-NEODYMIUM LASER PULSES

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Prepared for
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NOTICES

This final report was submitted by KRUG International, Technology Services Division, 406 Breesport, San Antonio, Texas, under contract F33615-84-C-0600, job order 7757-02-82, with the USAF School of Aerospace Medicine, Human Systems Division, AFSC, Brooks Air Force Base, Texas. Lt Col Robert M. Cartledge (USAFSAM/RZV) was the Laboratory Project Scientist-in-Charge.

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The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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INTRODUCTION

Several recent studies have investigated the nature of the laser-induced transient visual impairments known as "flashblindness" (1-5). In general, these studies have shown that the laser-induced loss of vision is qualitatively similar to that produced by noncoherent sources of similar luminous energy. One issue which has been extensively investigated in both laser and nonlaser flashblindness studies is that of "reciprocity" -- i.e., the tradeoff between the duration and intensity of the flash. Current findings indicate that, for single flashes, reciprocity extends from the briefest durations used (a few nanoseconds) to at least 100 ms and possibly as long as several seconds (1-3, 6-8). Practically, however, the upward temporal limit on predictable effects of intense light flashes is approximately 150-200 ms, or the time required for the blink reflex and saccadic eye movements to occur (9, 10). The extension of reciprocity into the submillisecond range is of great interest since a greater amount of unbleached pigment remains following equal-energy short flashes (a phenomenon known as "Rushton's Paradox") (11), thereby questioning the purported relationship between visual sensitivity and the amount of bleached retinal pigment.

A second type of reciprocity, involving the cumulative effects of a repetitive series of laser pulses, is also of considerable interest given the development of lasers with high repetition frequencies. It may be presumed that the effects of a series of flashes are largely additive (i.e., reciprocal) for extremely brief interflash intervals (IFIs), given that temporal summation in the visual system occurs up to 20 ms under photopic conditions (12). Since the empirically derived limit on bleaching by single flashes in the submillisecond range is approximately 50% (13), it is conceivable that a brief single flash may have even less of an effect than two or more flashes of equal cumulative energy which are presented at short IFIs (14). On the other hand, an extremely long IFI would allow for the return of pigment to its unbleached state and for the recovery of visual sensitivity, thus ensuring no additivity of the flash effects. In fact, a fundamental additivity has been shown to hold for IFIs of less than a few milliseconds (15), whereas little or no additivity has been shown for IFIs greater than 2 min (16, 17). Some evidence indicates that partial additivity may occur beyond 1 min (16), but this has been disputed (18). One difficulty involving intermediate and longer IFIs is the inverse relationship between pupil size and amount of bleached pigment, so that the increase in pupil size during recovery (which results in a progressively greater amount of light absorbed) counteracts the return of pigment to its unbleached state (which serves to reduce the additive component of the flash effect).

Little research has been conducted using repetitively pulsed flashes in the intermediate IFI range between a few milliseconds and a few seconds. A recent study using the visual evoked potential (VEP) in human subjects showed that a partial additivity may exist for a train of noncoherent light

pulses delivered within a 100-ms interval (19). The visual loss appeared to be an approximately linear function of the number of equal-energy flashes delivered. No research exists as to the flashblinding effects of a train of normally focused (collimated) Q-switched laser pulses below the maximum permissible exposure (MPE) for humans, which individually cannot produce any significant flashblindness (3). The purpose of this study, therefore, was to investigate whether the threat of multiple Q-switched laser pulses delivered within the interval preceding the onset of blink and other natural protective measures would be similar to that of a single pulse of equivalent energy.

METHOD

Subjects

Two adult rhesus monkeys (Macaca mulatta) were used as subjects in the present study. Prior screening ensured that neither of the animals had any abnormalities of the cornea, lens, or fundus, or a refractive difference between eyes greater than 1 diopter.

Visual Evoked Potential Recording

The VEPs were recorded from five bipolar depth electrodes in the two monkeys (three in one and two in the other). The characteristics of these electrodes and the procedures for implanting them have been described in previous reports (2-4). All electrodes were placed in the left striate cortex (area 17), and were situated in the central visual field projection area (0-2 deg). The VEPs were amplified using Grass 7P511 solid-state amplifiers at gains of 20,000 (for four electrodes) and 50,000 (for the other electrode). Low- and high-frequency filters were set at 1 and 100 Hz. A PDP 11/34 computer was used to digitize 1-s VEP epochs at a sampling rate of 256 Hz, and to perform a Fourier analysis of each averaged VEP.

The VEPs were elicited by a high-contrast (0.75), 2.0-c/deg square-wave grating which was temporally modulated at 3 Hz. The green-black grating was generated in the manner described previously (2), and was viewed at a distance of 1 m. The mean luminance of the grating was 7.5 cd/m^2. The VEP amplitude was calculated at 6 Hz (i.e., at the stimulus reversal frequency, or twice the frequency of the temporal waveform), as derived from the Fourier analysis.

The VEPs were recorded under pentobarbital anesthesia, using the same procedures as in previous experiments (2-4). The animal was paralyzed using Flaxedil, and was fitted with a contact lens which protected the cornea and provided optimal refraction. Only the right eye was used to view the gratings.

Laser Exposures

The optical system used in aligning and presenting the laser flashes was identical to that of previous studies, except that the frequency-doubled output (532-nm) of a Q-switched Quantel Model YG580 Nd:YAG laser was used as

the flash source in all exposures. The 10-ns collimated beam possessed a diameter of 1.6 mm, and was focused in a spot subtending less than 50 μm on the retina. The laser pulses were presented at a 20-Hz repetition frequency, and the number of pulses presented (either one or five) was determined by the duration of a Gerbrands 3001S digital timer (40 vs. 200 ms, respectively). Two energy levels for the laser exposures were used: 0.1 μJ and 1 μJ. These levels correspond to 50% and 500% of the MPE for humans, and were identical to those used in a previous flashblindness study involving single-pulse Q-switched laser exposures (3). In the case of the multiple exposures, the cumulative energy of the five pulses was equal to the energy of the single-pulse exposures; given the assumption of reciprocity inherent in the 1980 ANSI standard (20), this placed all exposure energies at the same levels relative to the MPE.*

Four exposures were made at each of the two energy levels and pulse-train conditions, and VEPs from the four exposure trials were averaged together. Each 210-s trial consisted of (1) two 30-s baseline intervals presented at the beginning and end of each trial, in which a homogeneous field of the same average luminance as the gratings was presented, (2) a 30-s stimulus epoch preceding the flash, and (3) a 120-s postflash stimulus epoch. The order of presentation of the four conditions was reversed for the second pair of trials and for the two monkeys.

RESULTS

The results from this study are illustrated both qualitatively in Figure 1 and quantitatively in Figure 2. In deriving the quantitative graphs, VEP amplitude measurements were made at 5-s intervals throughout the trial using a 1-s "sliding" offset. The VEP amplitudes for each electrode were then transformed into percentile values, with the lowest and highest VEP amplitude values throughout the trial set to 0% and 100%, respectively. The error bars define the 95% confidence limits for the final baseline, final preflash, and 5-s postflash intervals.

Whereas the single- and multiple-pulse exposures at 50% of the MPE produced a slight VEP loss which barely exceeded the 95% limits (Fig. 2a), both exposures at 500% of the MPE produced a much more pronounced decrement in VEP amplitude in the immediate postflash period (Figs. 1 and 2b). The waveform data in Figure 1 suggest that higher harmonic responses (reflected in the higher-frequency oscillations) were also greatly affected in the initial few postflash seconds. The single-pulse exposure appeared to produce a slightly greater effect than the multiple-pulse exposure, but this difference did not exceed the confidence limits in both cases.

Due to the 5-s averaging procedure, it was not possible to determine whether the partial VEP loss in the first 5 s following the flash reflected a brief but total loss followed by a rapid recovery, or a partial loss followed by a slower recovery over the 5-s epoch. To answer this question,

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*The assumption of reciprocity inherent in the ANSI 1980 standard was abandoned in the 1986 revision (21). According to the latter standard, the cumulative energy of the multiple-pulse exposure in this study would be equal to 57% of the MPE.

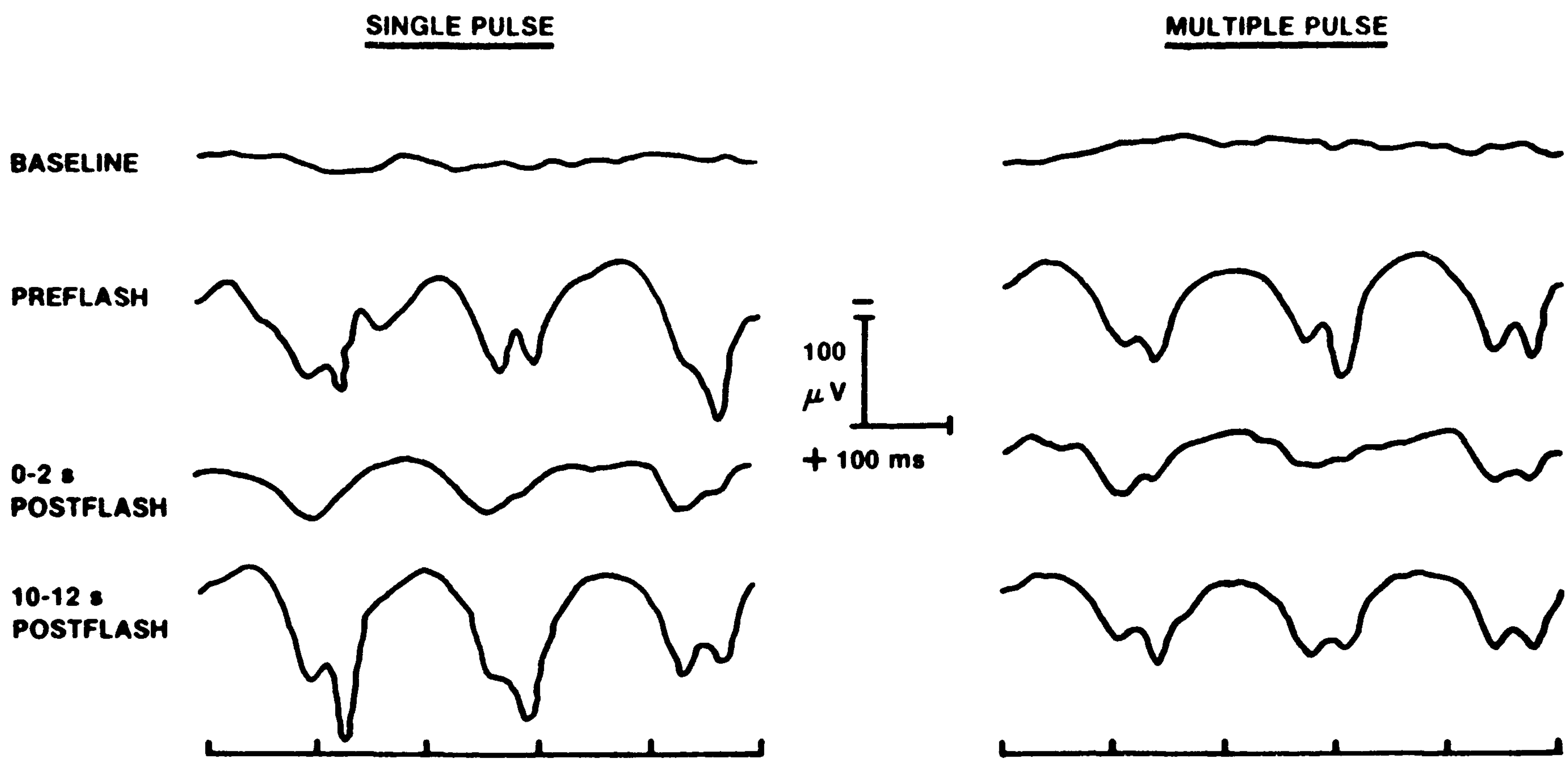

Figure 1. The effects of single-and multiple-pulse Q-switched doubled-neodymium laser exposures of equal total energy (500% of the MPE). VEPs were recorded from one electrode in monkey 413D in response to a 2.0 c/deg square-wave grating phase-reversed at 6 Hz. VEP traces represent an average of 4 responses.

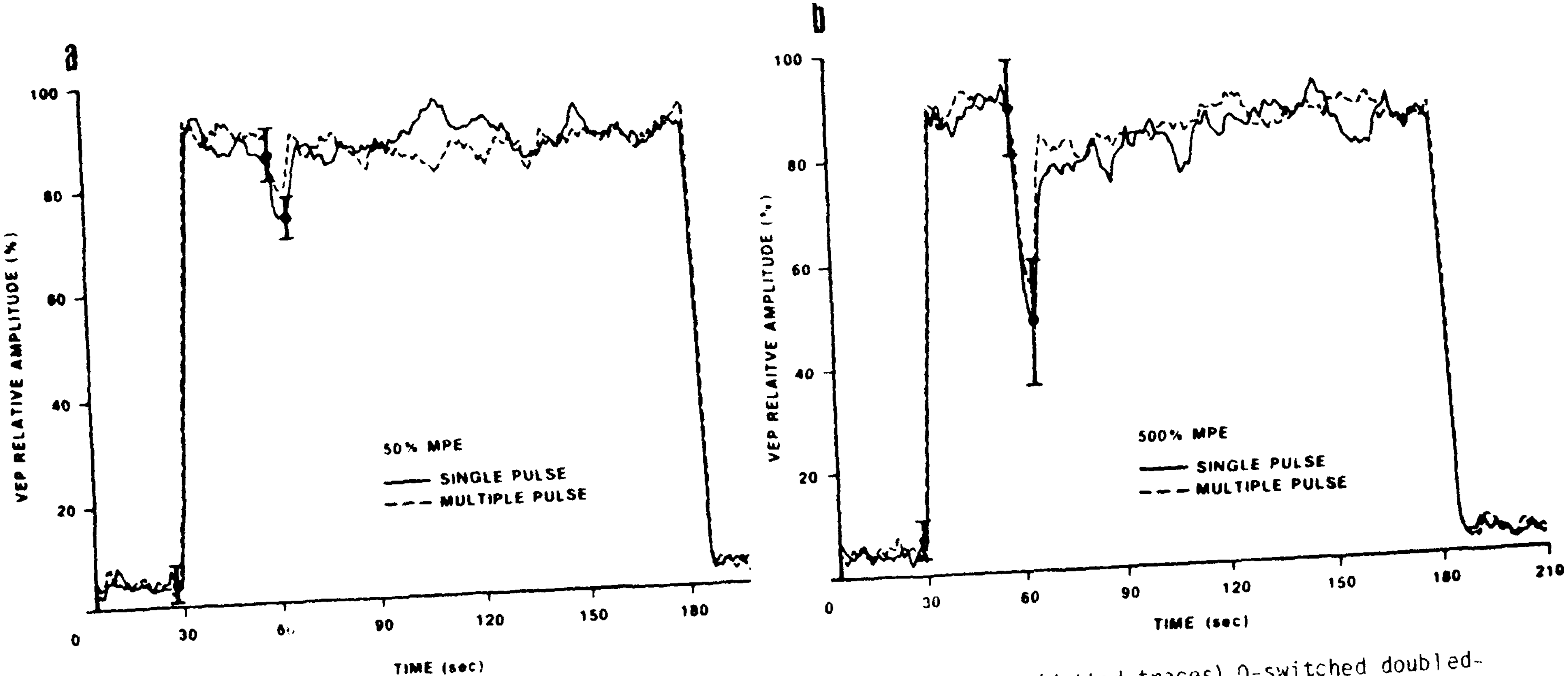

Figure 2. The effects of single-pulse (solid traces) and multiple-pulse (dotted traces) Q-switched doubled-neodymium laser exposures at 50% of the MPE (view a) and 500% of the MPE (view b). VEP relative amplitudes, averaged across all five electrodes, were derived as described in the text. The bars represent an estimate of the 95% confidence limits based on an average of the standard errors for each condition at the final baseline, final preflash, and initial 5-s postflash intervals. The flash was presented at 60 s.

the data from the single-pulse, 500%-MPE exposures were reanalyzed using a 1-s average. As shown in Figure 3, the partial VEP loss in the first 5-s postflash interval actually represented a brief, near-total loss followed by a rapid return to preflash amplitude by the end of this interval.

DISCUSSION

The major purpose of this study was to determine if single and multiple Q-switched laser pulse exposures produce similar effects when their overall energy levels are equated. The results indicate that the effects of the two types of exposures are fundamentally similar when the multiple-pulse train is delivered within a 200-ms interval.

The findings of this study are in basic agreement with those of Schmeisser (19), who demonstrated an additive effect of a series of noncoherent pulses delivered within a 100-ms interval. The flashes in that study were slightly longer (2 μs) and broader in retinal extent (~100 μm) than those used in this study. Nevertheless, the relationship between number of flashes and VEP amplitude reduction in the immediate postflash period was approximately linear, suggesting that a similar additivity holds for both the noncoherent flashes used in his study and the laser flashes used in this study. Thus, the combined effects of these two studies reconfirm the qualitative similarity between laser- and nonlaser-induced flashblindness which has been demonstrated in previous studies.

The findings of this study are also in basic agreement with the results of a prior Q-switched doubled-neodymium laser flashblindness study (3). In that study, a partial loss of VEP amplitude was demonstrated in the first few seconds following a collimated flash at 500% of the MPE, whereas no discernible effect was present at 50% of the MPE. By contrast, the effect of the 50%-MPE exposure in this study, though slight, did exceed the 95% confidence limits (which, however, were much smaller in the present study). While the loss of vision would be expected to be greater for a less-optimal target stimulus than was used in the present study, the region significantly affected by a collimated flash has been shown to be extremely small (2). Thus, it may be tentatively concluded from the results of this and previous studies that no significant loss of visual function will result from either a single- or multiple-flash Q-switched laser exposure if it remains collimated at the eye and does not actually damage the retina.

CONCLUSIONS

The transient loss of vision produced by a single Q-switched doubled-neodymium laser flash is similar in magnitude to that produced by a series of pulses of equal cumulative energy which are delivered within 200 ms. Thus, the results of this and previous studies suggest that a fundamental reciprocity between exposure energy and duration exists from the nanosecond range to at least 200 ms (the functional upper limit for flashblindness, given the duration of blink and eye movement protective mechanisms), and that this reciprocity appears not to be especially dependent on the number of flashes contained in the exposure.

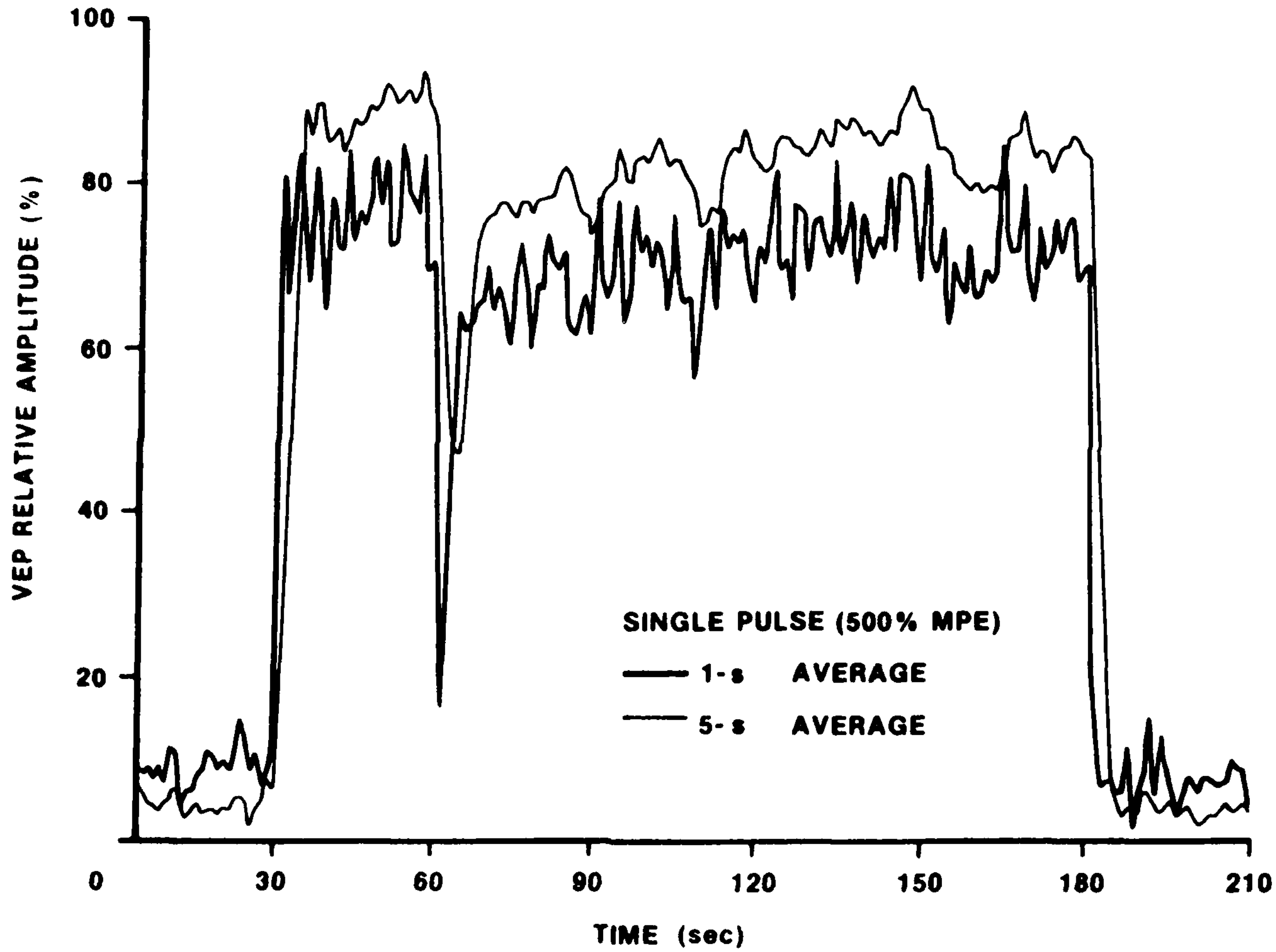

Figure 3. The effect of a single Q-switched doubled-neodymium laser flash at 500% of the MPE using a 1-s average (dark line) and a 5-s sliding average (light line).

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